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Influence of neutron surface on $E1$ resonance properties

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Abstract. The $E1$ strength distributions in even-even Si isotopes were calculated in the "particle-core coupling" version of the shell model taking into account the fragmentation of the hole configuration among the states of the daughter nuclei. The comparison of calculated strength distributions in different isotopes of the same element shows the peculiarities of a neutron surface influence on the $E1$ resonance fragmentation.

The problem of theoretical description of the excited states of light nuclei has been discussed for many years. Various model approaches have achieved success in the study of highly excited nuclear states, primarily $E1$ resonance, as this state is the most studied experimentally [1]. From comparison of the experimental photo-excitation cross sections it is seen that a consistent increase in the number of neutrons in the isotopic chain changes drastically the resonance structure. Especially, these changes are critical in the area of light nuclei $A < 50$, where the resonance structure is important. Theoretical description of dipole resonances in some even isotopes of Ti and Ca was performed in the previous paper [2]. In this work the structure of excitations of ^{28}Si and ^{30}Si isotopes is discussed.

1 Particle-core coupling shell model

The increasing amount of experimental data on structure of multipole giant resonances (GR) in the cross sections of nuclear reactions has shown that microscopic approach considering only particle-hole configurations cannot reproduce a complicated structure of GR. One of the possible ways to build a set of basic configurations which could be used as doorway states in the microscopic description of nuclear resonances is to take into account the distributions of the "hole" configurations among the states with total momentum J, excitation energy E and isospin T $(JET)_{A-1}$ of residual nuclei with mass number $(A-1)$. In the Particle Core Coupling version of Shell Model (PCC SM) these distributions are taken into account in microscopic description of multipole resonances (MR) [3, 4]. Theoretical description of MR in $1p$-shell nuclei based on the PCC SM has shown good agreement with experimental data for nuclei $7 \leq A \leq 15$ [4].

The wave functions of excited states of a nucleus in the PCC SM constructed as a product of the wave functions of the final nucleus $(A-1)$ and the wave functions of the nucleon

$$\left|J_f T_f\right\rangle = \sum_{J'E'T',j_f} \alpha_f^{J'E'T',j_f} \left|(J'E'T')_{A-1} \times (j_f) : J_f T_f\right\rangle. \quad (1)$$

The set of states of the final nucleus in (1) has to include all states with the significant genealogical connection to the ground state of the target nucleus

$$|J_i T_i\rangle = \sum_{J'E'T',i} C_i^{J'E'T',j_i} \left|(J'E'T')_{A-1} \times (j_i) : J_i T_i\right\rangle. \quad (2)$$

The way to determine the probabilities of the various core states which appear when one of the nucleons would be extracted from the parent nucleus is to use the experimental data on the spectroscopic factors S_i of direct pick-up reactions to estimate the coefficients of fractional parentage $C_i^{J'E'T',j_i}$

$$C_i = \sqrt{\frac{S_i}{\sum\limits_k S_k}}. \quad (3)$$

MGR probabilities could be calculated via the $E1$ form factors

$$F^2_{E1,T_f}(q) = \left|\left\langle J_f = 1, T_f, M_{T_f} \left\| O_1^{el} \right\| J_i = 0, T_i, M_{T_i}\right\rangle\right|^2,$$

where the excitation matrix element is expressed in terms of matrix elements of one-nucleon transitions

$$\begin{aligned}\left\langle J_f = 1, T_f, M_{T_f} \left\| \hat{O}_1^{el} \right\| J_i = 0, T_i M_{T_i}\right\rangle &= \sum_{i,j_f,j_i} \langle j_f \| \hat{O}_1^{el} \| j_i\rangle \times 3\sqrt{2} \langle T_i M_{T_i} 10 | T_f M_{T_f}\rangle \\ &\times \sum_{J'T'E'} C_i^{J'E'T',j_i} \alpha_f^{J'E'T',j_f} (-1)^{J'+j_f-1} W(01 j_i j_f; 1J') \\ &\times (-1)^{T'-T_i-1/2} W(T_i T_f \tfrac{1}{2}\tfrac{1}{2}; 1T') \end{aligned} \quad (4)$$

In Eq. (4), α_f are the results of the Hamiltonian diagonalization.

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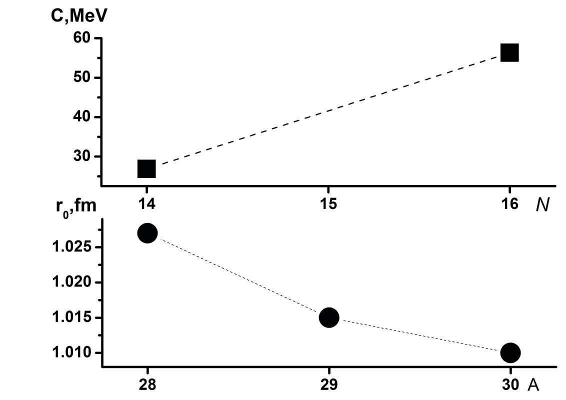

Figure 1. Rigidities C (up) and r_0 (down) of the stable Si isotopes.

2 Rigidities of Si isotopes

The distribution of hole states in the nucleus is highly influenced by the shape of nuclear potential well and its deviations from spheroid. In [5] was shown that the addition of neutron pairs to nucleus with given Z sometimes radically changes collective characteristics of nucleus. E.g. rigidity and hence surface tension of ^{48}Ca nucleus is about 10 times larger than these characteristics for ^{42}Ca or ^{44}Ca. The larger surface tension results in larger compression on nuclear matter and such nuclei are closer to spherical shape. The experimental distributions of hole state strengths along the energy axis for such nuclei are close to shell-model predictions for spherical nuclei. On the other hand, in nuclei with a low surface tension the Coulomb force deforms the potential well. Comparison of rigidities C for the ^{28}Si and ^{30}Si isotopes is shown in Fig. 1 together with parameters r_0 of their charge radii R_{ch}

$$R_{ch} = r_0 \, A^{1/3}. \quad (5)$$

The value of rigidity for ^{30}Si is about 2 times larger than for ^{28}Si.

The values of deformability for even-even Si isotopes are at least 10 times smaller then rigidity of ^{48}Ca. This difference in rigidities and, consequently, in surface tensions leads to great diversities in the distributions of the hole state strength. In Table 1, the occupancies $N_{nlj} = \sum_{nlj} S_i$ in the $2s-1d$ shell for ^{28}Si and ^{30}Si isotopes are shown. The values of N_{nlj} were obtained from direct pick-up reaction data (corresponding evaluated data are taken from Refs. [6, 7]). The (p, d) reactions on ^{28}Si show that not only $1d_{5/2}$ but the $2s$ and $1d_{3/2}$ hole states as well play an important role in excitation of this nucleus. For the ^{30}Si contributions of transitions from $1d_{3/2}$ subshell, contrary to the Single Particle Shell Model (SPSM) predictions, are more important then those from $2s$. Moreover, the $1d_{5/2}$ subshell is highly fragmented. The hole strength distributions for ^{28}Si, namely, the existence of low-lying $1/2^+$ and $3/2^+$ levels (0.78 MeV and 0.96 MeV, respectively), suggests a presence of oblate deformation in terms of the Nilsson model [8]. This assumption agrees with the experimental value of quadrupole deformation $\beta_2 = -0.42 \pm 0.02$ (see Ref. [9]). Comparison of the spectroscopic data for ^{30}Si with the Nilsson model predictions also suggests the negative deformation with $\beta = -0.2$ [10]. The recent predictions of various microscopic approaches gives $0 \geq \beta_2 \geq -0.4$ [11]. The hole distribution for ^{48}Ca [2] is close to the SPSM predictions for spheroid.

Table 1. Values of the occupancies N_{nlj} of the sub-shells in the $2s-1d$ shell for the ^{28}Si and ^{30}Si isotopes

Isotope	$1d_{5/2}$	$2s_{1/2}$	$1d_{3/2}$	sum
^{28}Si	4.71	0.64	1.15	6.5
^{30}Si	5.48	0.42	1.86	7.86

3 PCC SM results for ^{28}Si and ^{30}Si

The results of PCC SM calculations for $E1$ in the isotopes ^{28}Si and ^{30}Si are shown in Fig. 2 and 3 together with the experimental data from [12]. Figures 2(a) and 3(a) display the distributions of $E1$ form factors in ^{28}Si and ^{30}Si, respectively. Different types of shading indicate the type of transition giving a major contribution to $F^2(E_{exc})$. In Figs. 2(b) and 3(b), the calculated photo-neutron cross sec-

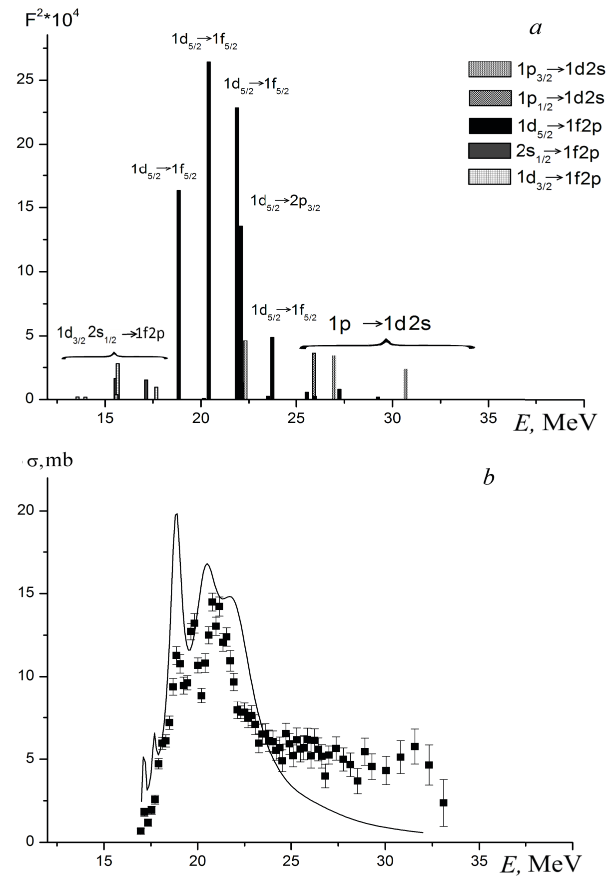

Figure 2. Form factors (a) and the estimated (γ, n) cross section (b) for ^{28}Si. Black squares – experimental cross sections from [12], solid line – the PCC SM calculations.

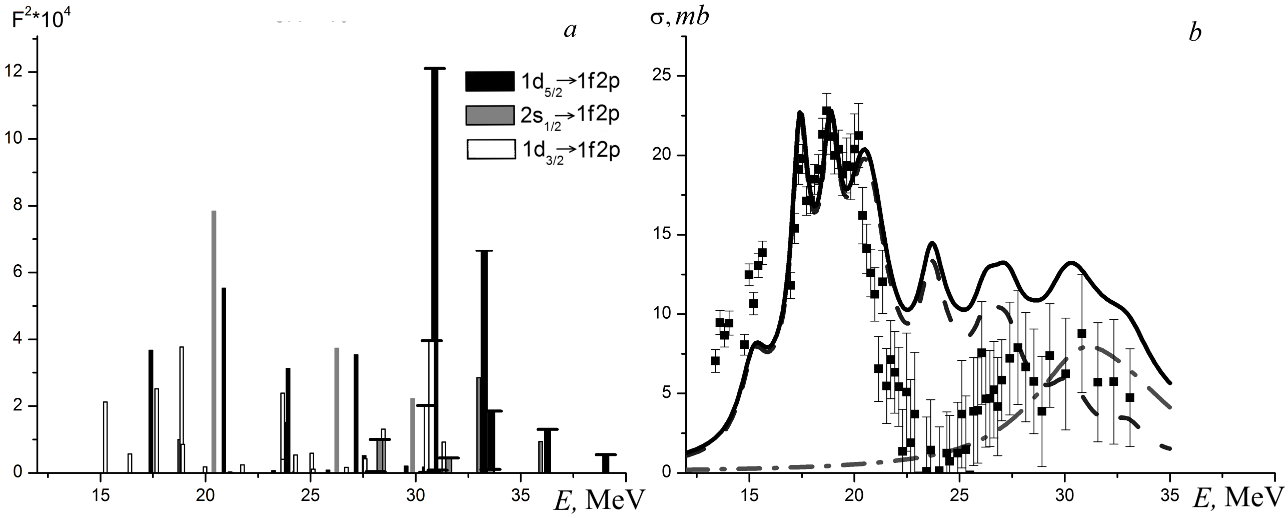

Figure 3. Form factors (*a*) and the estimated (γ, n) cross section (*b*) for ^{30}Si. Black squares – experimental cross sections from [12]; the PCC SM calculations: the dashed line – $T_<$ contribution, the dash-dot line – the $T_>$ one, the solid line – the total result.

tions for ^{28}Si and ^{30}Si (thin lines) and experimental data [12] are presented. As seen from comparison of theory and experiment, calculations for both the nuclei reproduce the main peculiarities of $E1$ in the energy region below $22-23$ MeV, i.e. at main peak and below. The "pygmy"-resonance region in ^{28}Si is populated by transitions from $1d_{3/2}$ and $2s$ subshells. The main peak of the $E1$ resonance in ^{28}Si is formed by transitions from $1d_{5/2}$ to $1f_{7/2}$ state. The pronounced splitting of the main peak is a consequence of fragmentation of $1d_{5/2}$ hole state. The emergence of an extra pair of neutrons in ^{30}Si leads to a considerable complication of the main $E1$ resonance peak structure due to additional transitions from the $2s$ and $1d_{3/2}$ states. In the structure of the $E1$ "pygmy" resonance of ^{30}Si (at $E < 18$ MeV) the transition from $1d_{3/2}$ hole dominates.

The region of $E1$ strength distribution above $24-25$ MeV cannot be properly reproduced since deep hole states in $A-1$ nuclei were not revealed in pick up reactions performed with low projectile energies (see [6, 7] and reference therein).

Excitation of $E1$ resonance in ^{30}Si leads to the appearance of states with the isospin values $T_> = 2$ and $T_< = 1$ (Fig. 3). For ^{30}Si the contributions of isospin branches to the cross section are comparable. The estimation for the difference between the average energies of $T_>$ and $T_<$ branches is about 7 MeV, which agrees with the assessment of isospin splitting based on experimental data [12].

The calculations of $E1$ strength distributions in ^{28}Si and ^{30}Si nuclei based on the Particle Core Coupling version of Shell Model show that the deviations of both nuclei from spherical form reveal in the splitting of main $E1$ peak and in population of "pygmy"-resonance area. Using experimental data on direct pick-up reaction spectroscopy allows one to trace the relationship of structural features of $E1$ resonance with effect of an extra pair of neutrons contribution.

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